JASON

Technical Report
JSR-79-14

February 1980

ON THE INTERACTION OF NON-IONIZING RADIATION WITH PEOPLE

By: Malvin A. Ruderman
Gordon J. MacDonald

SRI International
1611 North Kent Street
Arlington, Virginia 22209

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report examines the physical basis for many of the thermal and non-thermal interactions between microwaves and the human body. Although a microwave beam incident on the human body dissipates, on the average, about the same amount of heat as does normal metabolism, it can actually dissipate considerably more heat in certain local regions of the body because of strong beam focusing effects (e.g., within the brain), flow of induced currents through small, constricted areas of the body (e.g., ankle, neck) and differences in electrical properties among body tissues. Since relatively large heat dissipation can occur on a local level, it would appear more

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19. KEY WORDS (Continued)

20 ABSTRACT (Continued)

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For non-thermal processes, no special biological process or structure has been identified as likely to be especially sensitive to microwave fields or frequencies. The experimental results designed to explore the non-thermal effect of microwaves were studied. The results of all experiments purporting to demonstrate a significant non-thermal biological effect have been disputed; in fact, very few experiments in the entire field have ever been replicated -- a situation which should be rectified.

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ABSTRACT

This report examines the physical basis for many of the thermal and non-thermal interactions between microwaves and the human body. Although a 10 mW cm^2 microwave beam incident on the human body dissipates, on the average, about the same amount of heat as does normal metabolism, it can actually dissipate considerably more heat in certain local regions of the body because of strong beam focusing effects (e.g., within the brain), flow of induced currents through small, constrained areas of the body (e.g., ankle, neck) and differences in electrical properties among body tissues. Since relatively large heat dissipation can occur on a local level, it would appear more rational to determine a maximum permissive radiation exposure in terms of maximum allowed dissipation in a specific sensitive part of the body rather than, as is presently done, in terms of external beam intensity (the present U.S. standard is 10 milliwatts/cm^2).

For non-thermal processes, no special biological process or structure has been identified as likely to be especially sensitive to microwave fields or frequencies. The experimental results designed to explore the non-thermal effect of microwaves were studied. The results of all experiments purporting to demonstrate a significant non-thermal biological effect have been disputed; in fact, very few experiments in the entire field have ever been replicated -- a situation which should be rectified.

Finally, an intriguing set of experiments by R. Adey seem to indicate that an extremely low, modulated electric field affects the behavior of monkeys -- this result needs to be explored further theoretically and, especially, experimentally.

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I. INTRODUCTION

The possible biological effects of non-ionizing radiation have received wide public attention in recent years. Brodeur[1] called attention to the problem of the greatly enhanced use of microwaves in a two-part article in The New Yorker which he later expanded into a book carrying the sensational title, "Zapping of America". Young[2] had earlier expressed a layman's concern with the electric fields associated with high power transmission lines in his book "Power Over People". The mysterious microwave radiation of the American Embassy in Moscow has been noted by the press as well as being the subject of Congressional hearings[3]. The Navy's proposal to construct a ELF communication system, Project Sanguine and later Project Seafarer, stimulated research into the biological effects of low level electric and magnetic fields; see, for example, Schwan[4]. The public interest and the associated studies led the Comptroller General to call for greater protection from microwave radiation hazards[5].

At present there is no standard in the United States for human exposure to microwave radiation. The U.S. guideline for maximum microwave irradiation is 10 mW cm^{-2}. This is about 1/10 that of maximum sunlight. That portion of the microwave radiation which is not reflected at the surface of a 70 kg person gives an average internal power absorption at 0.3 W/kg, corresponding to a total body absorption of 20 watts, if diffraction effects are ignored. This is about 1/3 the heat dissipated from normal resting metabolism. Since

such an increase is easily accommodated when caused by exercise (or mild fever), the average body heating from such power dissipation has not been thought to be a cause for concern, and this has been used as a rationale for the 10 mW cm^{-2} guideline.

A large variety of effects, from much lower level microwave fluxes incident upon humans, has been reported by investigators especially within the USSR and Eastern European countries[6,7]. These include:

- o hypochondriasis
- o fatigability
- o unstable moods
- o "heavy feeling in the head"
- o loss of appetite
- o sleepiness
- o sleep impairment
- o irritability
- o mental disorders
- o memory difficulty

All of these can have other organic or psychosomatic causes. Reports of such microwave induced disturbances have generated controversy in the Western biomedical community, and the standards of different countries for acceptable microwave exposure of the general population reflect these uncertainties. (See Table I)

We examine the characteristic parameters and order of magnitude estimates relevant to the consideration of the interaction of microwaves with humans, and indicate some of the problems that arise in interpreting reported experimental results. This preliminary assessment does not investigate the numerous reports of "cooperative" mechanisms and other complicated biological processes which may be the ultimate determinants for safe fluxes.

	$mW\ cm^{-2}$
0.3 - 300 GHZ (CW) U.S.S.R.	10^{-2}
0.03 - 300 GHZ (CW) Poland	0.2
0.01 - 100 GHZ U.S. (guideline)	10
0.01 - 100 GHZ Canada, Great Britain	10
0.3 - 3 Sweden	1
PROPOSED N.Y.C.	0.1

TABLE I

RADIOFREQUENCY EXPOSURE STANDARDS

II. GENERAL HEATING AND COOLING

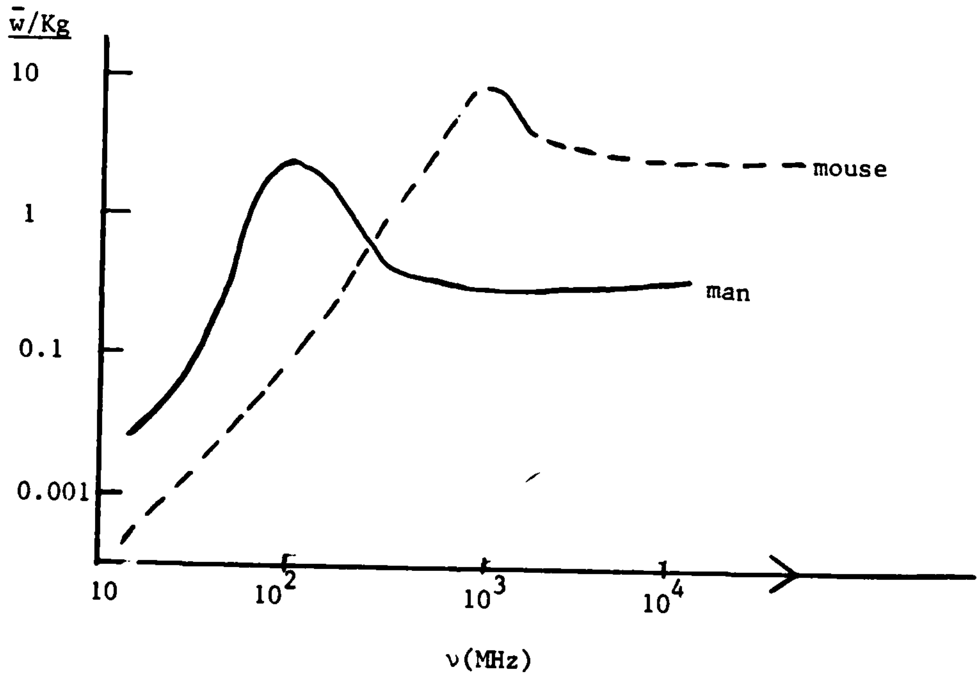
Resonant effects can be expected at frequencies $\nu \sim 10^2$ MHz when the radiation wavelength (measured in air), λ, becomes comparable to 2π times the body dimensions. This has been verified in detailed calculations with model bodies shown in Fig. (1).[8] Much below $\nu = 10^2$ MHz the very high conductivity and dielectric constant of human tissue ($\epsilon \sim 70$, $\tau \sim 10^{-2}$ mho cm^{-1}, similar to that of slightly salty water), causes almost complete surface reflection of the incident beam. At much higher frequencies the conductivity is less effective in causing surface reflection, but the high dielectric constant still keeps about 80% of the incident power from penetrating into the body. The peak absorption near $\nu = 10^2$ MHz corresponds to a total power dissipation within a person of 140 watts for incident 10 mWcm^{-2} radiation. At distances $(2n + 1)\ \lambda/4$ from nearby reflectors, the internal electric field may double and the internal power dissipation rise by a factor 4.

The thermal conductivity (κ) and heat capacity (c_m) of typical body materials are given in Table II.[8]

Material	Thermal Conductivities κ(cal/m sec/°C)	Specific Heat c_m (cal/g/°C)
Water	0.6	1.0
Brain	0.13	0.9
Muscle	0.12	0.8
Fat	0.05	0.6
Bone	0.35	0.5

TABLE II

THERMAL CONDUCTIVITIES AND SPECIFIC HEATS OF BODY TISSUES



(E is along maximum length)

FIGURE 1

AVERAGE ABSORPTION $\bar{w}$/Kg IN WATTS PER Kg OF BODY WEIGHT FOR INCIDENT 10 mW/cm^2

The time for heat to diffuse a distance $R>10$ cm in matter of density ~1 g cm^{-3} is

$$\tau \sim \frac{C\nu}{\kappa} R^2 > 2 \times 10^6 \text{ sec} \qquad (1)$$

In this time a power absorption of 140 watts could, if there were no heat transport except diffusion by heat conduction to the surface, raise 70 Kg of body tissue (water) by over 8°C. However, over macroscopic distances, R, it is blood flow that carries excees heat to the surface and lungs where cooling is effective (8% respiration, 40% convection, 45% radiation, 7% water evaporation). In exercise or other natural temperature raising processes there is increased metabolism, oxygen needs, and hence blood flow. General microwave power dissipation does not necessarily stimulate blood flow and the heat deposited may not be so easily disposed by increased rate of blood flow.

We note finally that regions of much richer or poorer blood supply (e.g., the lens of the eye) will, because of differential cooling, effectively be differentially heated even if microwave absorption were uniform.

III. CAUSES OF DIFFERENTIAL HEATING

Microwave absorption will generally not result in a uniform heating within the body for several reasons: differences in electrical properties among tissues; strong microwave beam absorption and hence screening, especially for GHz frequencies and above; beam focusing within the body causing relative "hot spots"; relatively large current densities through smaller areas of the body (neck, ankle, etc.). We consider some of these below.

The dielectric properties of various body tissues at $\nu = 100$ MHz are given in Table III[9] for the conductivity and the real part of the dielectric constant ϵ_o.

	Muscle Lung Heart Kidney	Brain	Fatty Tissue	Bone Marrow	Whole Blood	Plasma
σ	.01	5×10^{-3}	8×10^{-4}	2×10^{-4}	1.0×10^{-2}	1.5×10^{-2}
ϵ_o	70	70	10	7	70	80

TABLE III* σ in mho cm^{-1}

DIELECTRIC PROPERTIES OF BODY TISSUES

* Based upon Schwan, Ref. (9).

The conductivity σ and real dielectric constant ϵ_o are related to the complex dielectric constant by

$$\epsilon = \epsilon_o + \frac{1.8 \times 10^{12}}{\nu} \qquad (2)$$

The frequency dependence of ε_o and σ for brain tissue is given in Figure 2 and for muscle in Figure 3.

Power (P) in a microwave beam propagating through a medium with a complex dielectric constant ε falls off with distance x according to

$$P = P_o \exp\left(-\frac{4\pi\nu}{c} x \operatorname{Im}\varepsilon^{\frac{1}{2}}\right) \qquad (3)$$

Distances at which $P/P_o \sim \exp(-2)$ are given for various tissues as a function of frequency in Figure 4.[8] At $\nu = 3$ GHz that part of an incident microwave beam which is not reflected at the body surface is mostly absorbed by about 4 cm of fat or 1 cm of muscle, blood, or brain tissue. Its power, therefore, is far from uniformly deposited even in homogenous tissue models of the body. This effect is much less important at 10^2 MHz both because of the large penetration depth and because of the tendency of the diffracting incident radiation effectively to penetrate from all surrounding directions near resonance.

There can also be large variations in microwave power dissipation (σE^2) between adjacent tissues or organs because of their different electrical properties. A sphere of complex dielectric constant ε embedded in a medium of dielectric constant ε' has a power dissipation per unit volume (P) relative to that of its surrounding medium (P') given by

$$\frac{P'}{P} = \frac{\sigma' |E'|^2}{\sigma |E|^2} = \frac{\sigma'}{\sigma} \left|\frac{3\varepsilon}{2\varepsilon + \varepsilon'}\right|^2 \qquad (4)$$

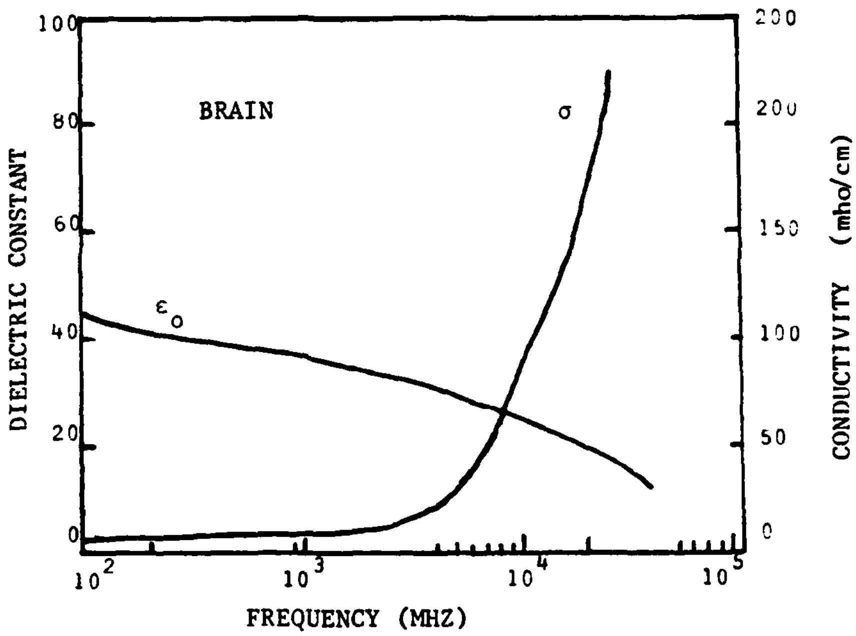


FIGURE 2

DIELECTRIC CONSTANT AND CONDUCTIVITY OF BRAIN IN THE MICROWAVE REGION[2]

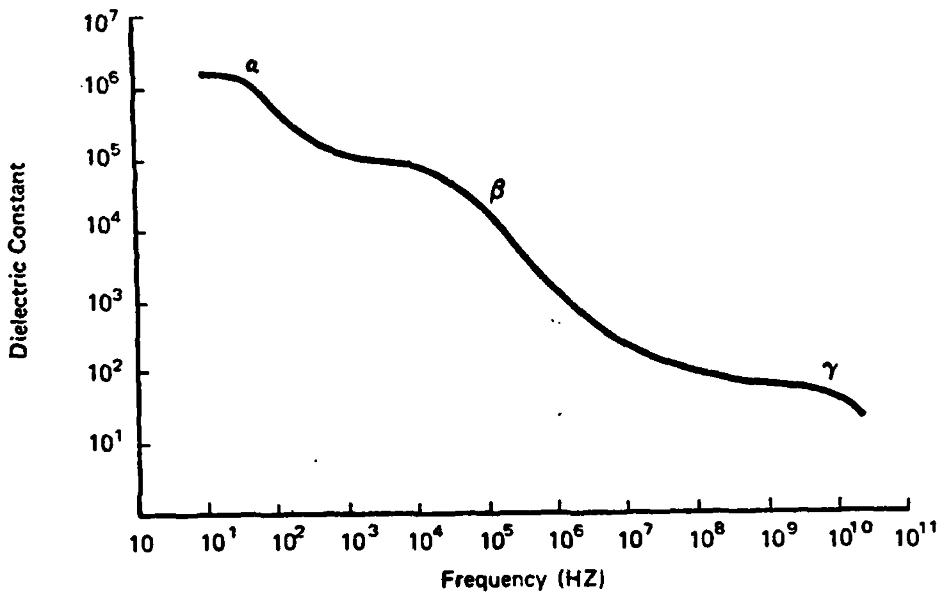


Figure 3

FREQUENCY DEPENDENCE OF THE DIELECTRIC CONSTANT OF
MUSCLE-LIKE BIOLOGICAL MATERIAL

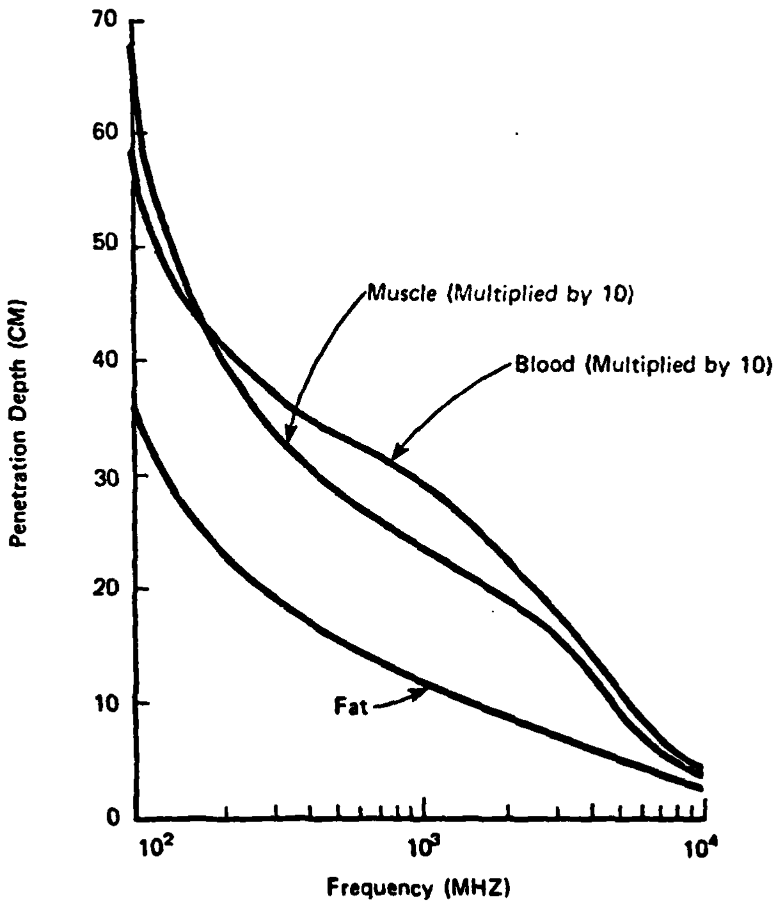


Figure 4

DEPTH OF PENETRATION IN BLOOD, MUSCLE AND FATTY TISSUE AS A FUNCTION OF FREQUENCY [8]

We see from Table III that this ratio can easily differ from unity by an order of magnitude for various types of inhomogeneities in body tissues. Whether or not this could be accompanied by temperature differentials of order 1°C or greater will be considered in Section IV.

At frequencies sufficiently high that $\lambda/2\pi$ is much less than characteristic body dimensions, geometric ray optics is a valid approximation for the internal propagation of microwaves. (At ν = 1 GHz, λ (vacuum)/2π = 5 cm.) Because the refractive index of tissue is so large, ($n = \sqrt{\varepsilon} \sim 10$), rays are bent almost normal to the body surface after entering. Thus an approximately round head in a parallel beam will focus such rays toward the center of the brain where local heating can be much greater than the average within the brain cavity. For a human brain in a 1 mW cm^{-2} 1 GHz beam (where the geometric approximation is only fair) the brain center dissipates 0.5 mW cm^{-3} while the average heating is only 0.1 mW cm^{-3} [8].

At lower frequencies where $\lambda \lesssim 2\pi R$ the incident electric field is approximately uniform over the body which will then act like a series of resistors. Narrow cross-sections, e.g., the neck, will have to carry essentially the same total current as the larger head and torso they connect. Therefore, since its resistance per unit length is higher, it will dissipate more ohmic heat. At 200 MHz with $\underset{\sim}{E}$ parallel to a man's height, computer stimulation gives a 9W/Kg heating in the neck for an incident 10 mW cm^{-2} microwave beam[8]. This

is an order of magnitude greater than the mean absorption rate over the entire body.

Clearly there are, then, a variety of circumstances in which a microwave beam, which, on the average dissipates about as much heat within the body as does normal metabolism, can in some parts of the body, dissipate well over an order of magnitude more. It would appear more rational to determine a maximum radiation exposure in terms of maximum allowed dissipation in any sensitive part of the body rather than in terms of external beam intensity.

IV. SOME CONSEQUENCES OF DIFFERENTIAL HEATING AND TEMPERATURE DISTRIBUTIONS

The distribution of dissipative heating within the body may affect biological responses for several reasons.

1) Body temperature control is centered in the hypothalamus at the base of the brain, but how this is accomplished is probably still only vaguely understood. It presumably depends not only on the temperature sensed directly by the hypothalamus, but also on nerve impulses received from peripheral parts of the body such as signals sent by sensors just beneath the skin surface. The entire body may respond differently to different inhomogenous temperature distributions in various organs when the body has the same average ΔT.

2) Local temperature perturbations significantly greater than the average may affect especially sensitive body constituents.

3) Even approximately uniform dissipative heating may build relatively large temperature differences in some parts of the body where, for example, blood circulation is inadequate to maintain uniformity.

A. Microscopic Effects

If microwave power is dissipated in a high conductivity region of radius R imbedded in a substance where dissipation is very much smaller, the steady state temperature perturbation distribution for $r \geq R$ is

$$\Delta T = \frac{P_o R^3}{3\kappa\ r}$$

where κ is the exterior thermal conductivity and P_o the interior power dissipation per unit volume. For $\kappa \sim 0.1$ cal m^{-1} $sec^{-1}/^{\circ}C$ from Table II and $P_o \sim 10^{-2}$ Wcm^{-3}, which is 5 times the average power dissipated at the 10^2 MHz absorption maximum from an incident 10 mW cm^{-2} microwave flux,

$$\Delta T \sim 3R^2 \left(\frac{R}{r} \right) {}^{\circ}C \qquad (5)$$

when R is measured in cm. With $r \sim R$ and $R \sim 10^2 \mu$, a characteristic distance between blood capillaries, $\Delta T \sim 3 \times 10^{-4}$ ($^{\circ}C$). Thus on any scale sufficiently small that blood flow is not the primary local cooling mechanism, differential heating would appear to be negligible.

B. MACROSCOPIC EFFECTS

On larger scales differential heating certainly can be important. Eq. (5) suggests that T can reach $1^{\circ}C$ when $r \sim R \sim 0.6$ cm. The best documented effect is cataract formation. The lens of the eye is a relatively large structure, not on the surface of the body, with exceptionally poor blood flow cooling. Excess heating causes cataracts. The threshold for cataract formation as a function of incident microwave power at 2450 MHz is given in Fig. 5. It would appear that this threshold is about a factor 10 greater than the suggested 10 mW cm^{-2} U.S. guideline. This threshold should, however, be used with care since at "resonant" frequencies near 10^2 MHz and/or at particular

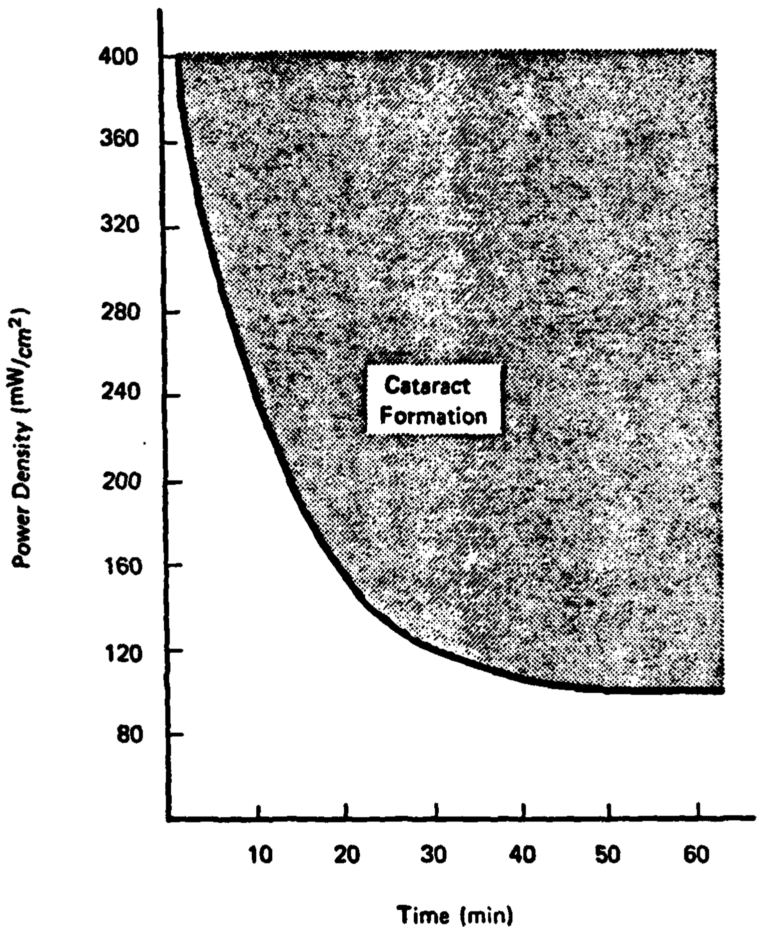


FIGURE 5

POWER DENSITY VERSUS TIME THRESHOLD FOR CATARACT FORMATION IN THE RABBIT FOLLOWING FREE-FIELD EXPOSURE AT 2450 MHz.

distances from reflectors the electric field energy density at the eye may greatly exceed that present in the absence of the body.

Another observed physiological response to pulsed microwave absorption is an auditory response probably caused by sudden thermally induced expansion within the brain cavity.[10]

It is not clear that any non-thermal effects have been categorically identified in biological organisms exposed to an incident flux less than 10 mW cm^{-2}. A number of hypotheses have been suggested for such effects, some of which we consider in Sections V and VI.

V. NON-THERMAL EFFECTS OF MICROWAVES ON BIOLOGICALLY ACTIVE MOLECULES

Several suggestions have been offered for ways in which microwaves in particular might have special effects on certain biologically important molecules. These include:

1) Formation of "poisonous" molecular states or free radicals from ambient atmospheric constituents. For example, significant formation of the excited singlet state of O_2 has been suggested as contributing a deleterious effect upon inhalation. There does not yet appear to be any experimental support for such an hypothesis.

2) Discrete resonances in molecular absorption in certain microwave frequency intervals. A distinctly quantum mechanical resonance (i.e., between, say, only two quantized energy states rather than between the almost infinite number in a harmonic oscillator) in some special biologically important molecule may exist between two states, whose energy difference is just $h\nu$.[11,12] But $h\nu/kT \sim 10^{-5}$ for $\nu \sim 10^2$ MHz. Therefore, there would be only a negligible effect on the thermal distribution between <u>two</u> relevant quantum states because of the addition of resonant microwave radiation.

3) "Classical" harmonic oscillator absorption by biomolecules. When a molecule possesses a vibrational degree of freedom, analogous to that of an harmonic oscillator, the resonant energy h can be absorbed between any two adjacent excited states.[11,12] An almost arbitrary amount of energy can, in principle, be pumped into this essentially classical degree of freedom. This energy is limited

ultimately by the finite relaxation time τ for energy to leave this mode and be shared with other degrees of freedom. This limiting steady state energy

$$\bar{\varepsilon} \sim \frac{8\pi e^2}{mc} \tau^2 P \tag{6}$$

where P is the incident microwave power, e the net charge of the vibrating element and m its mass. For the microwave flux to be important $\bar{\varepsilon} > kT$. With $P = 10$ mW cm^{-2} and m = a proton mass, this implies $\tau > 10^{-5}$ sec. Even with m, the electron mass, $\tau > 10^{-8}$ sec. Such a long relaxation time in condensed matter would be remarkable. Further, the line width $\Delta\nu \sim (2\pi\tau)^{-1} \sim 10^7$Hz would be so narrow that it would be missed in most microwave exposures (unless there were very large frequency shifts from different local environments of the relevant biomolecules, but then most molecules would be unaffected by a fixed frequency exposure.)

VI. ELECTRIC FIELD INTERACTIONS WITH CELLS

For a vacuum flux of 10 mW cm^{-2} the free electric field $E_o \sim 3Vcm^{-1}$; in tissue with $|\varepsilon| = |\varepsilon_o + 4\pi i\sigma/\delta| >> 1$ it is generally much less. We are therefore concerned with characteristic electric fields within the body of order 1 V cm^{-1} or less. This is actually a very weak field in the microscopic cellular regime and below. A single ion (in a vacuum) would give an electric field of 1 V cm^{-1} at a distance of 4μ . No effects have been identified in which such fields have been quantitatively estimated to be an important perturbation on natural processes within the body.

A. Local Membrane Effects

A typical cell contains an electrolyte ($\varepsilon_o \sim 60$) separated from an electrically similar environment by an insulating membrane whose capacitance is C ~ $1\mu f\ cm^{-2}$; this membrane consists of a lipid bipolar layer several hundred Å thick with a dielectric constant $\varepsilon \sim 5$[3]. The potential drop across a 1 $\mu f/cm^2$ capacitance is ~ 10^{-5} volts. This is to be compared to a typical normal resting potential drop across a membrane of several tens of millivolts or a similar variation in potential drop per ion if the fluctuation in its electrostatic energy is of order kT.

Coherence effects are insufficient to trigger nerve cell membrane breakdown at less than many hundred times the potential drop from the 1 volt cm^{-1} microwave field. Drift effects along a membrane for membrane ions have been observed for DC electric

fields of this order in large cells. Since the total potential drop along the membrane could then be of order kT this is not surprising, but such effects took over 10^3 sec to grow to substantial magnitudes[13,14] and thus would essentially disappear at microwave frequencies. A net flow of several hundred ions/sec has been estimated to flow through a cell membrane perturbed by a microwave electric field E_m of several V/cm[22]. But such flows will be quenched as soon as enough net charge has flowed to change the membrane potential drop by about $\Delta V \approx \Delta V_m\ (\Delta V_m/4kT)$ where ΔV_m is the membrane potential drop from an electric field E_m. For $\Delta V_m \sim 10^{-5}$ volts, $\Delta V \approx 4 \times 10^{-10}$ volts. This is accomplished by the movement of one hundred ions through the membrane. Thus the "weak" oscillating microwave field is not effective in altering the different ion concentrations across the membrane. No convincing mechanism for significant biological effects from local effects of "weak" high frequency fields on cell membranes has been discovered.

B. Induced Dipole Moments in Cells

In an approximately round volume V of electrolyte of complex dielectric constant ε_2 immersed in a medium of dielectric constant ε_1, an electric field E induces a dipole moment

$$\mu \sim \frac{3}{4\pi} V \frac{(\varepsilon_2 - \varepsilon_1)}{2\varepsilon_1 + \varepsilon_2} E \qquad (7)$$

For red blood cells immersed in blood plasma the measured difference in ε between whole blood (almost half red cells) and blood plasma suggests

$$\frac{\epsilon_2 - \epsilon_1}{\epsilon_1} \sim \frac{1}{10} \tag{8}$$

The induced dipole moments of cells in an impressed electric field E will cause cells to stick like a string of beads along an electric field[15] (and to repel each other in directions perpendicular to E) as long as

$$\frac{2\,\mu^2}{\epsilon_1\,R^3} \geq kT \tag{9}$$

with R the cell diameter.

Ellipsoidal cells will tend to orient themselves in an external electric field to minimize the interactive energy between their induced μ and E. The electrostatic energy of a disk with normal vector $\underset{\sim}{n}$ is

$$U = \frac{E^2}{8\pi} V\,(\epsilon_1 - \epsilon_2)\left[1 + \frac{\epsilon_1 - \epsilon_2}{\epsilon_1}\,(\underset{\sim}{n} \times \underset{\sim}{E})\right] \tag{10}$$

For orientation to be significant

$$(\epsilon_1 - \epsilon_2)^2\,\frac{E^2}{8\pi}\,\frac{\mathrm{Vol}}{\epsilon_1} \geq kT \tag{11}$$

For subcellular units this inequality is not at all close to being satisfied. (For example, triglycerides (fat) are often found in chyclomicrons up to 1μ in diameter. The left hand side of the inequality (11) for chylomicrons in blood and $E = 1\ \mathrm{V\ cm^{-1}}$ is 10^{-17} ergs, almost 4 orders of magnitude less than the right hand side).

For red blood cells, the needed inequalities for the above electric field effects to compete with Brownian fluctuations are

not satisfied unless the electric field exceeds about 20 V cm^{-1} (Fig. 6, Schwen[16]). To achieve such an internal electric field an incident microwave intensity of at least 1 watt cm^{-2} would be needed. Even then, as discussed below in subsection D, hydrodynamical effects could easily swamp any alignment or stringing tendencies. (These would only be expected to be important for cells which are free to move in a fluid environment).

C. Positional Forces

Because of possibly large variations in dielectric constant between blood and some of the body matter it is in contact with, electric fields may, for certain geometrical configurations, vary greatly over small distances. This can, in principle, have effects on the movement of a cell through such regions. An hypothetical example is shown in Fig. 7 for an electric field of strength E_o within a medium of bone marrow ($\varepsilon \sim 7$) interlaced with flowing blood ($\varepsilon \sim 70$).

At position 2, the electric field

$$E_2 \sim E_o \varepsilon_m / \varepsilon_b \sim E_{10/10} << E_o \tag{12}$$

but at position 1, the electric field is much larger:

$$E_1 \sim E >> E_2 \tag{13}$$

A blood cell with dielectric constant ε_c surrounded by plasma with ε_{pl} has an extra electrostatic energy in a field E of

$$U \approx (\varepsilon_c - \varepsilon_{pl}) \frac{\varepsilon^2}{8\pi} \text{Vol} \tag{14}$$

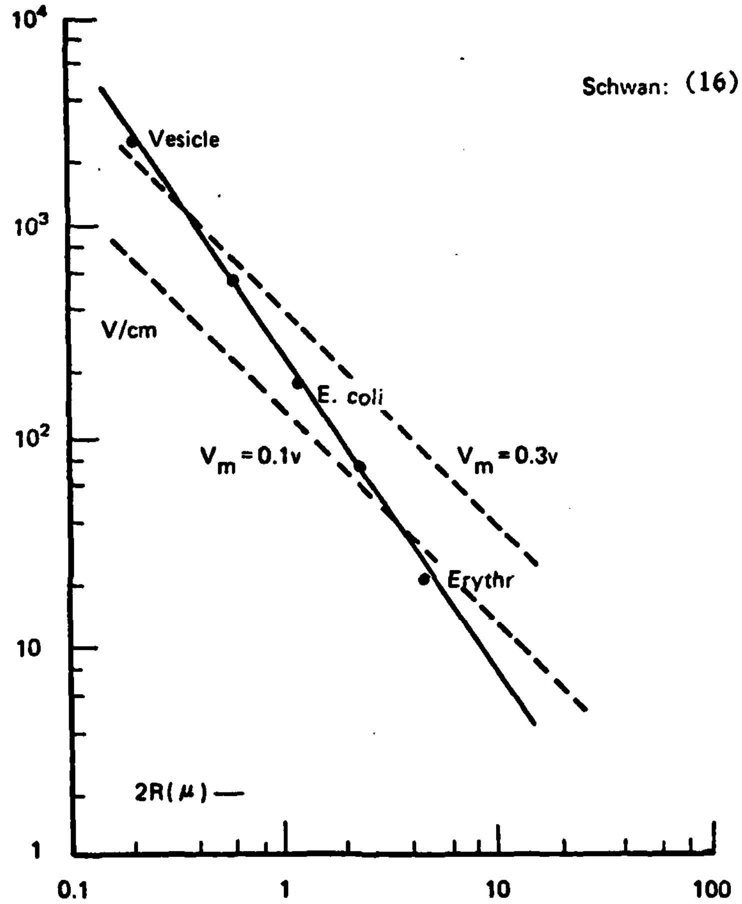


FIGURE 6

Threshold of field effects on particles and cells. The solid curve gives the threshold for field-generated force effects. The dashed curves give the threshold for dielectric membrane breakdown, assuming two different values for the membrane breakdown potential. Some typical membrane breakdown potentials listed by Schwan are of the order of 200 mV. For erythrocytes Zimmermann et al. give a breakdown potential above 1000 mV. Data given are for permeability changes in chromaffin granule vesicles (Neumann & Rosenheck), orientation and pearl chain formation effects in E. coli and erythrocytes (Sher & Schwan and pearl-chain formation threshold data for silicone particles (solid points, Sher & Schwan), axis: particle diameter.

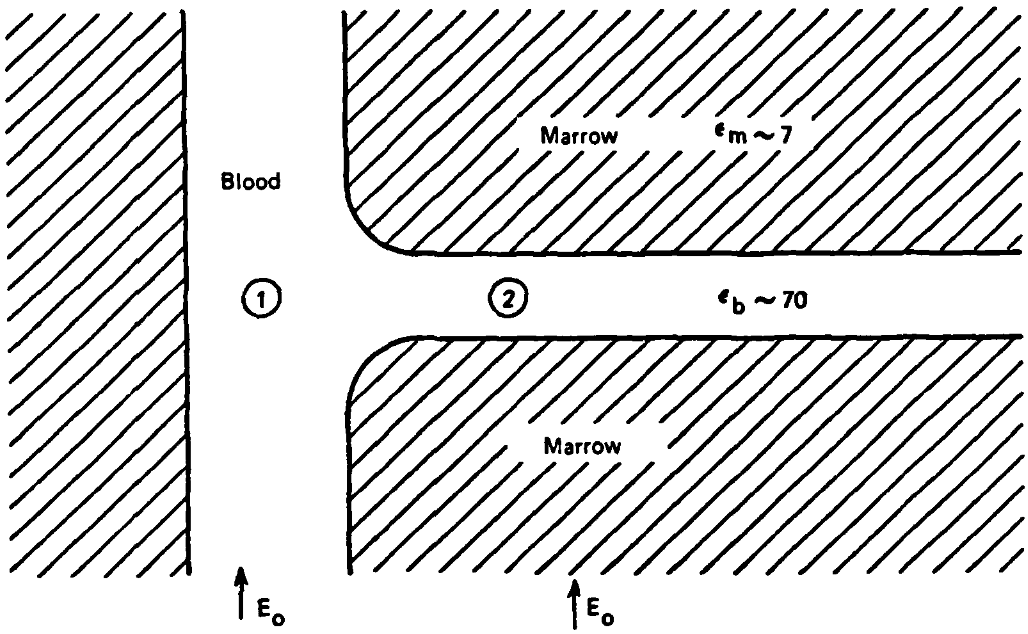


FIGURE 7

SCHEMATIC FOR BLOOD CELLS AT TWO POSITIONS
IN CAPILLARIES WITHIN BONE MARROW

Then the difference in electrostatic energy for a cell at position 1 relative to the same cell at position 2 is

$$\Delta U = U_1 - U_2 \sim U_1 \sim \frac{\epsilon_{pl}}{\epsilon_c - \epsilon_{pl}} \, \Delta U_{orient} \qquad (15)$$

where ΔU orient is the orientation energy of Eq (10). Therefore

$$\Delta U \sim 10 \times \Delta U_{orient} \qquad (16)$$

This ΔU associated with changes in cell position is accomplished over a distance comparable to the diameter of a capillary which, in turn, is not much larger than that of a red cell.

Thus, for special geometries and environments, the forces on a cell caused by the electric field gradients from tissue inhomogeneities are the largest that can be accomplished by microwaves. But the resulting energy differences are still very much below kT. Moreover, not only is the effect on cell motion still very much smaller than that from Brownian motion, but it is also very much less than that from the shear flow of the transporting plasma.

D. Comparison with Hydrodynamic Effects

Tendencies toward orientation and "stringing" of cells may be significant mainly if the cells are free to move in a surrounding fluid as is the case for cells in blood plasma. However, hydrodynamic effects from the fluid motion will also cause cell motions which can be very much larger than any caused by electric fields.

For example, a typical flow speed (V) in a capillary is about 10^{-1} cm s^{-1} at the center and zero at the boundary of a 10μ radius (r) capillary. The velocity shear is then

$$\frac{\partial v}{\partial r} \; \frac{10^{-1} \text{ cm s}^{-1}}{10\mu} = 10^{2} s^{-1} \tag{17}$$

and the velocity difference across an R = 5 cell which almost fills a capillary is

$$\Delta v \cong R\frac{\partial v}{\partial r} = 10^{-1} \text{ cm s}^{-1} \tag{18}$$

Then for a fluid density $\rho \sim 1$ gcm^{-3},

$$\partial(\frac{\partial v}{\partial r} R)^2 \sim 10^{-2} \text{ ergs cm}^{-3} \tag{19}$$

This is a measure of hydrodynamic energy associated with changing the aspect of a cell to the fluid flow around it. This may be compared to an electrostatic energy density of order $\left|\varepsilon_1 - \varepsilon_2\right|\frac{E^2}{8\pi} \sim 10^{-5}$ ergs cm^{-3}, smaller by three orders of magnitude. Therefore, the hydrodynamic drag and torque on such cells is of order 10^3 that from microwave electric fields of 1 V cm^{-1} and would be expected to dwarf such electrostatic effects.

E. Comparison with Magnetic Effects

The magnetic field of a 20 mW cm^{-2} microwave beam is 10^{-2} G, much less than the ambient field of the earth. However, it is relatively easy to put large (10^4 G) magnetic fields through a body, which are 3 x 10^6 times larger than the microwave electric fields of interest. We consider next whether the presence or absence of biological effects from such magnetic fields can give

any clue to those which might be expected from the weak microwave electric fields.

F. Microwaves in Living Brains

What has been omitted from the estimates of Sections VI. A to VI. D is possible consequences of the coherence of microwave electric fields over distances $c(2\pi\nu\varepsilon)^{-1}$ [4.10^{-2}cm in brain tissue at 4.10^{9} Hz]. In some circumstances, this could, for example, act along a nerve dendrite in such a way that a potential drop of 40 mV might obtain from an internal field of 1 V/cm. Or the coherent electric field might resonate at certain frequencies with parts of the brain nerve network. Or responses of an entire cell membrane, as opposed to individual molecules in it, may have unexpected features in certain frequency intervals. Thus, for example, when N molecules act coherently Eq. (6) is altered with $e \rightarrow Ne$ and $m \rightarrow Nm$ so that $\bar{\varepsilon} \propto N$. Then energies in special modes can be enormously greater than kT for sufficiently large N. But present understanding of the complicated biological systems is so primative that it seems best for now to rely entirely on experiments for indications of effects of this sort.

Static electric fields do not penetrate into the conductor which is the human body. It is only because microwaves have a high frequency (comparable, in cgs units, to the body conductivity) that their electric fields may influence some human biological processes. But magnetic fields are almost unaffected by the small magnetic

susceptibility of the body ($\mu - 1 \sim -7 \times 10^{-7}$ for water and similar values presumably hold for the relevant organic tissues). Therefore steady magnetic fields penetrate easily. We have seen that typical effects of an electric field E are proportional to $(\Delta\varepsilon)^2 E^2 \varepsilon^{-1}$, where $\Delta\varepsilon$ is a difference in dielectric constant across some interface. A generous estimate is obtained with $\Delta\varepsilon \sim \varepsilon \leq 80$ so that with $E = 1$ V cm^{-1}, $(\Delta\varepsilon)^2 E^2 \varepsilon^{-1} \sim 10^{-3}$ erg cm^{-3}. But with a magnetic field $\Delta\mu \sim 10^{-7}$ so that B must be greater than 10^5 G to give a similar effect -- a regime in which there is no long-term biological data.

In summary, for incident microwave intensities of less than 10 mW/cm^2 which give internal electric fields of about 1 V cm^{-1} or lower, none of the above discussions of non-thermal physical effects support the view that they may be biologically important. No special biological process or structure has been identified in this survey as likely to be especially sensitive to microwave fields or frequencies. We turn next to a brief consideration of the results of some experiments and observations of consequences of microwave irradiation of living species that raise questions as to whether or not there are indeed non-thermal microwave sensitive biological processes.

VII EXPERIMENTS AND OBSERVATIONS

Detailed comprehensive surveys of claimed biologic and pathophysiologic effects of exposure to microwaves have been published by S. Michaelson[6] and others[16,17,18]. We consider below only some additional summary remarks and considerations not discussed there.

The epidemiological evidence based upon exposures of radar technicians is at best inconclusive . The USSR reports, which are difficult to evaluate, do not appear to be accepted as compelling evidence by most Western investigators. Early reports of excessive Downs syndrome in the progeny of radar workers have not been supported by more extensive data. There now does not seem to be any excess mortality among radar repairmen relative to that among radar operators.

Microwave diathermy has been extensively used as therapy for a variety of complaints. A study of exposures in Pinellas Co., Florida[17] indicated about 50,000 treatments/month on the back, neck and arthritic sites of patients. Typically patients received 4-10 treatments of 5-30 minutes each of intensity 50 to over 200 mW cm^{-2} at 2.4 GHz microwaves, enough to feel "mild warmth." The penetration depth at that frequency is from about 5 cm (fat) to 2 cm (muscle), so that radiation would not be absorbed at considerable distances from a locally radiated site (critical reflection would keep most of it from escaping from the body once it had entered.) While no ill effects from these therapeutic microwave irradiations have been

documented, apparently there has not been any organized or intensive study of possible consequences.

Microwave frequency CB radios held close to the head can give electric field strengths which reproduce that of powerful external microwave irradiations[20]. Here, too, possible biological consequences have apparently not been reported though we are not aware of any studies.

Laboratory experiments on monkeys, mice, and lower life forms to explore possible non-thermal effects of microwave irradiation are generally controversial for several reasons:

1) Experiments, as a rule, are simply not repeated by different experimental groups. Different protocols are usually used even in the rare cases where a similar experiment is repeated on the same species.

2) Temperature control is generally not precise. Most reported effects might be caused by a temperature rise of order 1^{o} somewhere in the tested organism. (The existence of an effect is not necessarily disputed, only whether it has a <u>non-thermal</u> origin).

There appears to be no single experiment purportedly demonstrating a significant <u>non-thermal</u> biological effect of incident microwave fluxes of order 10 mW cm^{-2} which has been reported by several different groups and not disputed.

Candidates for non-thermal effects include changes in the permeability of the blood-brain barrier, in the Ca^{++} eflux from

the brain cells of decapitated chicks, immune system effects, teratology in insect pupae, and more. Many of the relevant experiments claim significant results at a variety of frequencies including ELF (extremely low frequencies). A full summary is given by Adey and Bawin in Ref. 24. The results are intriguing and puzzling. For example, Adey, et al[22] report an increase of up to about 10% in isolated chick forebrain 45 Ca^{++} eflux when subject to 147 MHz microwaves. However, this significant effect is reported to be present when the incident power exceeds 0.1 mW cm^{-3} but not if it exceeds 2.0 mW cm^{-2}. Moreover, it is not seen unless the microwave beam has a modulated amplitude with modulation frequency between 5 and 25 Hz. A similar power - modulation frequency window is reported at ELF. Here a decrease in Ca^{++} eflux is reported but only for electric field amplitudes in the window between 0.1 V cm^{-1} and 1 V cm^{-1} and for frequencies between several Hertz and several tens of Hertz. These are the ELF frequencies and fields typical of those used by Adey[22] in experiments designed to see if monkey behavior could be altered by ELF electric fields. But here a special paradox exists. These fields were maintained by a condensor whose parallel plates were far from the monkeys. But body tissue is such a good conductor and high dielectric at low frequencies that almost none of the externally applied field could possibly have penetrated into the monkey brain. For example, a spherical shell of small thickness Δ and complex dielectric constant ϵ subject to an external field E allows a field E_1 to penetrate into its enclosed volume with

$$E_i \cong \frac{3R}{2\varepsilon\Delta} E_o \qquad (20)$$

In Adey's experiment $\nu = 7$ Hz, $E_o \sim 10^{-1}$ Vcm^{-1}, and $\varepsilon \sim 10^6 + 10^8 i$. Since $R \sim 10$ cm and $\Delta \sim 10^{-1}$ cm a hollow skull cavity could have contained only about 10^{-7} V cm^{-1}; and a filled brain would have $E_i \lesssim 10^{-9}$ V cm^{-1}. It is difficult to understand how such a minute internal electric field (10^9 times less than that characteristic of microwaves radiation) could have biological consequences. Typical spontaneous brain electric fields are several orders of magnitude larger than 1-10 mV cm^{-1}.

The existance of a brain response to ELF electric fields of 10^{-7} Vcm^{-1} is probably the critical question in considering modulated microwave brain effects. If it is verified, then it may be reasonable to expect that ELF modulated microwave beams are much more effective in achieving the same brain response that is an unmodulated microwave beam. This could come about, for example, if the interaction of the ELF electric field is with an aligned array of unsymmetrical molecules (such as is found in a cell membrane). The dielectric constant of such an array is of the form

$$\varepsilon = \varepsilon_1 + \varepsilon_2 \, E/10^8 \text{ V cm}^{-1} + O(E^2) \qquad (21)$$

if the molecules are so arranged that they are all oriented in the same direction along E. An electric field of strength 1 V/Å = 10^8 V cm^{-1} is that which would greatly polarize a typical atom or molecule. Then E^2 can be of order unity for such an array. A dielectric constant of

the forms (21) will then give an ELF component for strongly ELF modulated microwaves. The ELF field amplitude will be of order 10^{-8} that of the incident microwave beam and 1 V cm^{-1} at ELF modulated microwave frequency would give an equivalent 10^{-8} V cm^{-1} at ELF. Similar effects might then be expected from the ELF modulated microwaves and the ELF waves. In the former, the beam gets into the brain without great diminution, but the small non linear response of which demodulates it, gives a small ELF component. It is, however, near that which would have penetrated into the brain for directly incident ELF of the same 1 V cm^{-1} external field strength as that of the microwave beam. This may be similar to the sort of effects reported by Adey, et al at ELF and microwave frequencies.

In the absence of plausible mechanisms or even promising potential candidates for non-thermal biological effects from 10 mW cm^{-2} microwave irradiation, the experimental situation is frought with controversy: it just does not yet appear to contain a convincing body of reproduced experiments which are without thermal contamination, the sort of evidence needed to compel belief among skeptics of non-thermal biological effects from 1 V cm^{-1} microwave fields. But, if exceptionally interesting results such as those reported by Adey and coworkers, should also be pursued and confirmed in other laboratories, it would be clear that extraordinarily weak fields in living brain tissue can produce important effects with important consequences for establishing

thresholds for modulated microwave beams far below those for unmodulated beams.

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REFERENCES

1. P. Brodeur, New Yorker, Dec 13, p. 50; Dec 20, p. 43, 1976

2. L. Young, Power Over People, Oxford University Press, New York, 1974

3. Irradiation of the American Embassy, Moscow, Washington Monthly, October, 1977

4. H. Schwan, Naval Weapon Laboratory Report NWL TW-2713, 1972.

5. More Protection from Microwave Radiation Hazards Needed, GAO Report HRD-79-7, 1978

6. S. Michaelson, "Trans. of the Int. Microwave Power," Inst. 8, 15 (1978)

7. S. Baranski and P. Czerski, Biological Effects of Microwaves, Dowden, Hutchinson and Ross, Stroudsburg, Pa., (1976)

8. J. C. Lin, "Trans. of the Int. Microwave Power," Inst. 8, 55 (1978)

9. H. Schwan, in Physical Techniques in Biological Research, W. Nastuk, ed., Vol. VI, Part B, (Academic Press, New York) 1963

10. K. Foster and E. Finch, Science, 256 (1974).

11. J. Eyster and E. Prohofsky, Phys. Rev. Letters, 38, 371 (1977).

12. E. Prohofsky, Physics Letters, 63A, 179 (1977)

13. L. Jaffe, Nature, 265, 600 (1977).

14. M. Poo and K. Robinson, Nature, 265, 602 (1977)

15. P. Tyler, "Biologic Effects of Nonionizing Radiation," Annals NY Acad. of Sciences, 247, (1975)

16. H. Schwan, Annals of the N.Y. Acad. of Sciences, 303, 198 (1977)

17. Survey of Diathermy Equipment Use in Pinellas, Florida, 1970 HEW: BRH/NERHL 71-1

18. D. I. McRae et al, "A Technical Review of the Biological Effects of Nonionizing Radiation." Report to the Office of Science and Technology Policy (1978)

19. D. Hazzard, Symposium on Biological Effects and Measurements of Radio Frequency/Microwaves (1977), HEW Publ. (FDA) 77-8026.

20. H. Lewis, JASON Summer Study Note, "CB Irradiation of the Brain", 1978

21. S. Bawin, and R. Adey, in Ref. (13) P. 305.

22. W. Ross Adey, in "Behavior and Brain Electrical Activity", N. Burch and H. Altshuler, Eds. (Plenum Press, N.Y.) 1975

23. S. Barnes, and C. L. Hu, Trans. Microwave Assn. (9 Sept. 1977)

24. W. Ross Adey and S. Bawin, Neurosciences Res. Prog. Bull. 15, No. 1 (1974)

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